APPENDIX D

Contributions of Accelerator Science and Technology to Office of Energy Research Programs

D. 1. Accelerator Physics—A Brief Overview

Particle beams are essential tools of modern science and technology. From the early experiments of Roentgen and Rutherford to present times, X-rays, gamma-rays, electrons, protons, neutrons, and alpha particles have been used to explore the structure of matter, to probe the interactions among the components of matter, and to further numerous medical and technological applications. Advances in the development of particle accelerators and continuing progress in particle-beam physics underlie the ever-increasing utility of these tools.

A particle beam is a particular state of matter, consisting of a large ensemble of particles having nearly the same momentum. The average direction of the momentum defines the direction of propagation of the beam, and usually all the particles are of the same type—for example, they are all electrons or they are all protons.

Historically, the idea of a beam derives from light optics, where the physical properties of light rays have been studied for centuries. Many of the basic concepts for particle beams are carried over from the optics of light beams. As in optics, accelerator science is the study of beam sources, beam propagation and the systems used to focus and bend beams, and the interaction of beams with matter. In most cases, however, the particles in a beam are electrically charged; this introduces many new properties not found in light beams. Charged-particle beams can interact with electromagnetic fields ranging from the fields of a resonant cavity to those of a laser beam. Particles can gain energy through this interaction and thereby be accelerated to high energies. This property has led to the development of particle accelerators that serve to greatly increase the velocity and therefore the energy of particle beams.

The development of particle accelerators during the last roughly 50 years has been striking. From the first electrostatic accelerators, which accelerated particles to a few hundred keV, to present TeV colliders, particle energies have increased by seven orders of magnitude. Experiments are now exploring matter at a scale length of about 10^{-18} m, which is about one-thousandth the size of a proton. Synchrotron radiation sources based on electron or positron storage rings are producing X-ray beams with more than one trillion times the brightness of X-ray tubes, thus leading to new insights into the structure of materials and biological molecules. Intense low-energy neutron beams, produced by high-current proton accelerators, are being used to study the structure of materials, and extensions of these accelerators are being considered for defense applications.

This progress has been made possible by research into the physical properties of particle beams and the development of accelerator technology. Most of this research and development is applied work, done in a context established by the anticipated use.

Dealing as it does with unique states of matter and physical configurations, accelerator research often has much broader implications than suggested by the original applied motivation. Spin-offs and applications based on accelerator technology have significant impact on the U.S. Department of Energy (DOE) programs, biomedicine, industry, and the national economy. Examples include applications to medical diagnostics and therapy using electron, proton, and X-ray beams; to structural molecular biology studies; and to heavy-ion fusion and plasma heating in the fusion program.

Another, quite different consequence of accelerator physics research has been its seminal contributions to an entirely new field of research. Studies of the motion of charged particles in nonlinear electromagnetic fields (that is, fields that vary rapidly with position) contributed to the discovery of one of the most active fields of modern physics, nonlinear physics, whose implications range from the motion of planets and stars to biology—anywhere there are questions of long-term stability and the onset of chaotic behavior. Even today, particle beams remain one of the best systems for pursuing combined, detailed theoretical and experimental studies of single-particle and multiple-particle nonlinear dynamics.

Studies of the nonlinear behavior of beams are an example of basic research that uses beams and their properties outside a context set by an anticipated use. Far less effort and funding is devoted to such basic research than to applied accelerator research, but for several reasons, it is an important contributor to the health and vitality of accelerator physics and technology. First, basic research encourages creativity by removing boundaries set by an anticipated use. In addition, it offers a broadened perspective that research can have long-range impacts even when no short-term benefit is envisioned. And finally, since basic research is naturally pursued in universities, it assures the benefits of the free-ranging inquiry typical of academia, together with the vitality and new ideas that students bring to the field.

The Office of Energy Research (OER) high energy physics program has supported this type of basic research, and it has led to many important results, including the development of superconducting materials, magnets, and RF cavities; very-high-gradient accelerating structures; and methods for studying the nonlinear dynamics of particle beams. More details of these results are given in Appendix F.

The role that accelerators play is different for each of the five OER research programs. In the following sections, we describe the role of accelerator science and technology in each of these programs.

D. 2. High Energy Physics

High energy physics studies the fundamental structure of matter and the laws governing the interactions of the basic constituents of the universe. Recently, experiments in underground laboratories have studied solar neutrinos, the long-term stability of the proton, and related phenomena, but the great majority of high energy physics experiments have been and are still done with high energy accelerators.

During the 1950s and 1960s, all high energy physics accelerator-based experiments relied on scattering primary or secondary beams from a fixed target. During this period, the development of strong-focusing accelerators led to a large increase in beam energy, from a few GeV at the Cosmotron and Bevatron in the 1950s, to 30 GeV at the Alternating Gradient Synchrotron (AGS) at Brookhaven National Laboratory (BNL) and the Proton Synchrotron (PS) at the European Laboratory for Particle Physics (CERN) in the early 1960s. There followed the multihundred-GeV Main Ring at Fermi National Accelerator Laboratory (Fermilab) and the Super Proton Synchrotron (SPS) at CERN; the development of GeV-level lepton colliders in Europe, the U.S., and the Soviet Union; and a 30-GeV proton collider, the Intersecting Storage Ring (ISR), at CERN. The colliders soon reached a luminosity that allowed them to explore small-cross-section events, leading to an ever-increasing use of colliding-beam experiments in place of fixed targets.

The next phase, beginning in the 1980s, has been characterized by the construction of very-high-energy colliders: the Tevatron at Fermilab, the Stanford Linear Collider (SLC) at the Stanford Linear Accelerator Center (SLAC), and the Large Electron-Positron Project (LEP) at CERN and by the development of very-high-luminosity lepton colliders, such as the Cornell Electron Storage Ring (CESR) at Cornell. The present phase continues this trend with the construction of B-factories in the U.S. and Japan, substantial upgrades of the Tevatron and CESR, and construction of the Large Hadron Collider (LHC) at CERN.

Currently, the U.S. high energy physics program centers on fixed-target experiments at BNL, Fermilab, and SLAC, and on collider experiments at Fermilab, SLAC, and Cornell. A description of the basic characteristics and performance of these facilities is given below.

Major U.S. High Energy Physics Facilities

	Fixed-target Facilities		Colliding-beam Facilities	
BNL	AGS (p)	30 GeV		
	AGS (polarized p)	22 GeV		
SLAC	Linear accelerator (polarized e^-)	50 GeV	SLC (e^+/e^-) (polarized e^-)	50 GeV/beam
			B-Fact. (3-GeV e^+ on 9-GeV e^-)*	
Fermilab	Tevatron (p)	800 GeV	Tevatron (p/pbar)	900 GeV/beam
Cornell**			CESR (e^+/e^-)	8 GeV/beam

* Under construction; expected to be completed in FY1998.
** National Science Foundation supported; majority of outside users are DOE supported.

The Fermilab proton-antiproton collider, where the top quark was recently observed for the first time, is currently the highest-energy collider in the world, and it will remain so until the LHC at CERN starts to operate around 2005, at an energy of about 7 TeV per beam. The SLC at SLAC was the world's first linear collider and has been used to study the Z particle using polarized beams. To bring the SLC to the luminosity level needed to study the Z has required the development of new accelerator physics and technology, which will be essential for future TeV-class linear colliders. CESR at Cornell is the world's highest-luminosity electron-positron collider. It has been used to study the properties of B particles and, at the same time, develop the accelerator physics and technology needed for the next generation of very-high-luminosity colliders, which will be used for the study of Charge Conjugation Parity (CP) violation in the decay of B particles and phi particles. At Brookhaven, following a period of extensive and innovative improvements to the AGS, the facility now provides proton beams at the highest intensity available in the world. These intense beams are being utilized for experiments studying very rare decays of K mesons, the anomalous magnetic moment of the muon with high precision and for many other precise measurements.

In the last 15 years, it has become widely accepted that lepton colliders based on storage rings cannot exceed the LEP energy in a cost-effective manner because of synchrotron radiation losses. The solution to this problem is the linear collider, which was developed initially at SLAC, and whose development continues now in a large international collaboration involving the U.S., Japan, and Europe. Two main approaches to linear colliders are being pursued, one based on high-frequency, room-temperature accelerating structures (being studied mainly at SLAC and the National High Energy Physics Laboratory of Japan [KEK]), and a second based on lower-frequency superconducting structures (being pursued by the TESLA collaboration involving Deutsches Elektronen Synchrotron [DESY], other European laboratories, and Fermilab).

The next-generation proton colliders (for example the LHC) are still based on storage rings, using high-field superconducting magnets. Synchrotron radiation will reach a significant level in this collider and would certainly be very important in colliders with energies above 50 TeV. In the long run, circular hadron colliders will also be limited by synchrotron radiation losses.

This process of developing ever-larger accelerators with ever-larger energies—and at ever-higher costs—has been accompanied by a dramatic decline in the number of operating accelerators and high energy physics laboratories. In fact, most present research is concentrated in four laboratories in the U.S., two in Europe, and one in Japan. This trend will likely continue in the next decades.

Since high energy physics depends so strongly on the development of higher-energy and higher-intensity accelerators and colliders, accelerator R&D has always been an important part of this DOE program. In 1962 the Division of Physical Research of the Atomic Energy Commission (AEC) set up a formal program in accelerator R&D, and, as a result, the AEC/Energy Research Development Agency (ERDA)/DOE Division of High Energy Physics has always had a budget line item for accelerator physics and technology. A High Energy Physics Advisory Panel (HEPAP) subpanel (the Tigner Panel) was established in 1980 to review accelerator R&D and to look at the future of accelerators and colliders. The Tigner Panel recommended establishment of a separate effort within the DOE high energy physics program for long-term accelerator R&D. This program funds research groups at national laboratories, universities, and industry and provides the main support for training graduate students in accelerator physics. This is described in more detail in Appendix F.

D. 2. 1. Funding and Users

Research in high energy physics is supported mainly by the DOE, with additional support from the National Science Foundation (NSF). Fermilab, SLAC, and BNL are DOE laboratories, while Cornell is supported by the NSF. DOE funding for high energy physics is approximately $600M (in 1995 dollars). In recent years, funding has decreased for accelerator operations, with consequent reductions in personnel and accelerator running time at the DOE laboratories.

Numbers of users from U.S. universities, national laboratories, and foreign institutions of the three major U.S. high energy physics facilities are given in the following table:

Users of U.S. High Energy Physics Accelerator Facilities

	U.S. Universities	U.S. Laboratories	All Foreign	TOTAL
BNL	295	98	120	513
Fermilab	1227	171	647	2045
SLAC	332	186	280	798
TOTALS	1854	455	1047	3356

In addition, DOE's High Energy Physics program supports Brookhaven's Accelerator Test Facility (ATF) and Argonne's Advanced Accelerator Test Facility (AATF) and its direct successor, the Argonne Wakefield Facility (AWF), which are user-oriented facilities that focus on studies of new acceleration concepts. Presently, the ATF has a total of about 40 users and the AWF about 12.

D. 3. Nuclear Physics

The goal of nuclear physics research is to understand, at a fundamental level, the structure and dynamics of strongly interacting matter, its properties under a wide variety of conditions in the laboratory and the cosmos, and the forces that govern its behavior. Nuclear physics depends largely on the use of accelerators for its experimental investigations. Corresponding to the great diversity of the field, a relatively large number of accelerators are employed, of greatly varying size, age, and type. Nuclear physicists use beams of ions from protons to uranium nuclei, radioactive beams, and secondary beams such as pions or kaons, as well as electrons.

During the 1950s and 1960s, nuclear physics experiments relied on small accelerators at universities, such as cyclotrons and Van de Graaffs. As the requirements for beam energies, intensities, and, especially beam species grew, additional larger dedicated facilities were built at universities and at the national laboratories. The Los Alamos Meson Physics Facility (LAMPF) was the premier nuclear physics facility in the U.S. for many years. At the same time, the use of high energy physics facilities played a significant role: The Lawrence Berkeley National Laboratory (LBNL) Bevatron was modified to become the Bevalac, the first high energy heavy-ion accelerator, and SLAC accommodated some nuclear physics experiments, as did Fermilab.

Recently, two of nuclear physics' key scientific objectives—understanding the quark structure of nucleons and nuclei and the search for the quark-gluon plasma—have demand higher currents and duty factors for electrons, and higher currents and energies for heavy ions. This motivated the construction of two large facilities designed specifically for nuclear physics at these research fronts: the Continuous Electron Beam Accelerator Facility (CEBAF) in Virginia, a continuous wave (CW), high-current electron accelerator of moderately high energy, which has recently become operational, and the Relativistic Heavy Ion Collider (RHIC), a dedicated high energy heavy-ion collider.

CEBAF is a superconducting, recirculating linac designed to deliver continuous electron beams of up to 200 mA of current, polarized and unpolarized, simultaneously to three experimental areas. CEBAF's design energy is 4 GeV, but operational experience with the superconducting cavities indicates that an energy of up to 6 GeV may be possible within a few years and that a push into the 8- to 10-GeV range will be possible at modest expense. Research at CEBAF is aimed at understanding nuclei and nuclear forces in terms of quantum chromodynamics (QCD), which describes the interactions of the underlying fundamental constituents, quarks and gluons.

Now under construction at BNL, RHIC is the first colliding-beam facility specifically designed to accommodate the requirements of heavy-ion physics. When completed in 1999, RHIC will provide heavy-ion collisions for a range of ion species up to gold, with beam energies of 30 to 100 GeV/nucleon. Collisions between unlike ion species will also be possible at constant nucleon energies. Projected luminosities vary with ion species and range from about 2×10^{26} cm^{-2} -s^{-1} for gold beams to 10^{32} cm^{-2} -s^{-1} for protons. The facility will support up to six interaction regions, with two major detectors and two smaller experiments approved for initial operation. Research at RHIC will attempt to explore the equivalent of a liquid-gas phase transition for quantum systems where hot, dense nuclear matter becomes a quark-gluon plasma.

A number of smaller accelerator facilities with unique characteristics and capabilities constitute an important component in the nuclear physics program. The DOE supports programs at Massachusetts Institute of Technology (MIT), Argonne National Laboratory (ANL), LBNL, BNL, and Oak Ridge National Laboratory (ORNL). The Bates Laboratory at MIT uses a pulsed electron linac and stretcher ring for experiments with internal polarized targets and polarized electrons. The ATLAS heavy-ion linear accelerator at ANL is based on low-velocity superconducting cavities and provides high-quality heavy-ion beams from hydrogen to uranium for nuclear structure research. The 88-Inch Cyclotron at LBNL provides heavy-ion beams for nuclear structure research from a state-of-the-art high-charge-state electron cyclotron resonance ion source. A fixed-target heavy-ion experimental program at BNL uses the AGS proton synchrotron in an incremental fashion around the long-running high energy physics program. A first-generation Isotope On-Line (ISOL)-type radioactive beam facility (now under development) is based on the ORIC cyclotron and 25-MV folded tandem at ORNL.

Nuclear physics facilities at Michigan State University (MSU) and Indiana University are supported primarily by the NSF. MSU has three superconducting cyclotrons at National Superconducting Cyclotron Laboratory (NSCL). The K500 was the world's first superconducting cyclotron. The K1200 is the world's highest-energy (~10 GeV) CW cyclotron and has been used in support of the nuclear physics program since 1988. The MSU cyclotrons and the DOE-supported cyclotron at Texas A&M are used for research on nuclear fragmentation, the nuclear liquid-gas phase transition, and in-flight radioactive beams.

The Indiana University Cyclotron Facility (IUCF) is active in areas of beam-cooling technologies and polarized proton beams. Two cyclotrons provide protons with energies up to 200 MeV for direct beams, as well as serving as the injector complex for the Cooler Ring. This ring can accelerate protons to an energy of 500 MeV. The distinguishing characteristic of this facility is the availability of polarized beams in all machines. The Cooler Ring has a state-of-the-art electron-cooling system capable of providing very dense beams, which are used for dedicated accelerator physics experiments related to the intensity frontier.

Several smaller accelerators at universities do important experiments in nuclear structure and nuclear astrophysics, and provide training for graduate students in a direct, hands-on manner: Triangle Universities Nuclear Laboratory (TUNL), University of Washington, and Yale (all DOE supported), and Florida State, Texas A&M, Notre Dame, Princeton, and SUNY Stony Brook (all NSF supported).

With two new major accelerator facilities under construction (RHIC) or coming into operation (CEBAF), limited effort is going into new nuclear physics facility initiatives. CEBAF has a development effort in superconducting RF technology and engineering with a goal of reliably achieving accelerating gradients of 10 to 15 MV/m for an eventual boost in CEBAF energy. The NSCL facility at MSU has proposed to couple the K500 and K1200 cyclotrons to increase the output beam currents by orders of magnitude. The recent Nuclear Science Advisory Committee (NSAC) long-range plan recommended the development of ongoing radioactive ion beam capabilities through the immediate upgrade of the MSU facility, together with a design study for and future construction of a next-generation radioactive beam laboratory based on the ISOL technique. In addition, they encouraged support for a Light Ion Spin Synchrotron facility based on the existing IUCF infrastructure.

D. 3. 1. Funding and Users

The recently completed long-range plan for nuclear physics in the United States is based on outyear projections of funding for nuclear physics by the DOE of \$325–\$350M (in 1997 dollars) and by NSF of a constant level of effort starting from the FY1994 budget. The FY1996 DOE budget for nuclear physics is \$304.5M.

Numbers of users from U.S. universities, national laboratories, and foreign institutions (for most recent year reported) are given in the following table:

	U.S. Universities	U.S. Laboratory	All Foreign	TOTAL
RHIC	225	120	377	722
AGS	256	94	119	469
CEBAF	287	87	168	542
ATLAS	173	55	82	310
Bates	199	16	49	264
IUCF[1]	292	81	60	433
MSU[2]	290	79	138	507
HRIBF	123	66	74	274[3]
88-Inch	71	96	46	237[4]
TOTALS	1916	694	113	

1–Users reported for period 1990-93.
2–Users reported for period 1988-95.
3–Eleven industrial users included in total.
4–Twenty-four industrial users included in total.

D. 4. Basic Energy Sciences

The mission of DOE's Basic Energy Sciences (BES) program is to expand the scientific knowledge and technical skills needed to aid long-term economic growth and to develop new and existing energy resources. The role of accelerators in BES programs in Materials Sciences, Chemical Sciences, Engineering and Geosciences, and Energy Biosciences has increased greatly during the past two decades. Twenty years ago, no accelerator-based user facility was supported by BES. The first synchrotron light source to be supported by BES was the National Synchrontron Light Source (NSLS), for which construction began in 1978. The first accelerator-based neutron source was the Intense Pulsed Neutron Source (IPNS), which began operation in 1982.

In carrying out its mission, BES now supports activities at the DOE national laboratories to design, construct, and operate major accelerator-based user facilities. These include four of the nation's eight synchrotron light sources (the Advanced Light Source [ALS] at LBNL, the Advanced Protron Source [APS] at ANL, the NSLS at BNL, and Stanford Synchrotron Radiation Laboratory [SSRL] at SLAC) and the two U.S. pulsed neutron sources (the IPNS at ANL and the Los Alamos Neutron Scattering Center [LANSCE]). The 7-GeV APS synchrotron light facility at ANL is now being commissioned. BES also supports two reactor-based neutron sources not included in the scope of this report. In addition, DOE supplied most of the funding to construct the light source at Louisiana State University (LSU), the CAMD facility, but DOE supplies no operating funds for this facility.

At present, no new light sources or neutron sources are under construction; however, beamlines are being added at existing light sources. In addition, BES supports programs using electron microscopes and ion-implantation facilities. In FY1996, BES will support the development of a conceptual design for a 1-MW spallation neutron source.

The other four light sources in the U.S. (the NSF-supported CHESS facility at Cornell University, the SURF II facility at th National Institute of Standards and Technology [NIST], the NSF-supported Aladdin facility at the University of Wisconsin, and the CAMD facility at LSU) are all smaller than any of the BES/DOE facilities. In addition, a 1-GeV ring has recently begun operation at Duke University, which will be used as a VUV free-electron laser driver, as well as a source of synchrotron radiation. Among possible future resources is a 2.5-GeV light source, proposed at North Carolina State University. Proposals for linac-based, short-wavelength free-electron lasers have been developed at BNL (λ > 750 Å) and SLAC (λ > 1.5 Å).

Over the past two decades, BES has acquired considerable experience and expertise in constructing, operating, and improving their accelerator-based user facilities. The broad, multidisciplinary research at these facilities is conducted by scientists supported by BES, other OER programs (particularly the Office of Health and Environmental Research [OHER]), other DOE programs (for example, Environmental Management [EM] and Defense Programs [DP]), other agencies (including the NSF and the National Institutes of Health [NIH]), and industry. BES experience with user facilities has broadly benefited OHER, which funds beamlines (including the insertion device source) optimized for its user community at BES-supported facilities. In some cases, the funding for a beamline is shared by OHER and BES, where it is relevant to the missions of both programs.

D. 4. 1. Neutron Scattering

Neutron scattering is an important tool for R&D in condensed-matter science, including the life sciences, materials science, and chemistry. Experimental possibilities are limited by the intensity of the neutron sources, which fundamentally determines the achievable signal-to-noise ratio in any experiment. One of the major strengths of neutrons as probes of structure, dynamics, and magnetic properties is the fact that they are indirectly ionizing and hence nondamaging to many materials of interest. Thus, all gains in intensity are gains in capability. As accelerator R&D moves forward, thereby providing the technology for more powerful neutron sources, new opportunities are sure to emerge in applying neutron scattering to biological, materials, and chemical research.

For many years, reactors have been the mainstay of neutron beam applications. However, the development of high-flux reactors has reached a level where further enhancement of source fluxes has become very difficult. The Advanced Neutron Source (ANS) proposed a factor of five increase in neutron flux beyond that achieved in present sources. This step proved to be extremely technologically challenging and costly, contributing to the demise of this proposal.

Beginning about 25 years ago, high-current, medium-energy proton accelerators were built which could drive spallation sources of sufficient intensity to compete favorably with reactors. In particular, pulsed sources could provide peak fluxes exceeding that available in reactors. However, such sources required development of time-of-flight techniques if they were to be effective in scientific applications. Pulsed-source and instrumentation development has since proceeded apace. Four very effective pulsed spallation sources are now operating worldwide (two in the U.S.), and efforts are under way in the U.S., Europe, and Japan to design even more powerful sources.

In the early years, the pulsed sources were viewed as unique in providing high instantaneous fluxes and short pulses of epithermal (0.05–10 eV) neutrons, especially useful in diffraction and high-energy transfer spectroscopy. Experience rapidly showed that cryogenic moderators at pulsed sources are highly effective sources of cold neutrons, while also advantageous at the epithermal energies. As a consequence, thermal and cold neutron time-of-flight methods have been developed that parallel capabilities at reactors and compete advantageously or even excel them in many scientific applications. New accelerator-based sources have been considered that could provide time-average slow neutron fluxes comparable to the reactor fluxes. Some facility concepts are simultaneously adaptable to providing intense, short pulses and high-time-average fluxes.

At present there are four operating pulsed spallation sources and one nearly complete steady-state spallation source as described in the table below:

Accelerator-Based Neutron Sources

Facility	Location	Beam parameters	Power	1st Year of Operation
SINQ	PSI/Switz.	600 MeV × 1300 µA	780 kW	1996
ISIS	RAL/U.K.	800 × 200	160	1985
LANSCE	LANL/U.S.	800 × 60	48	1985
IPNS	ANL/U.S.	450 × 15	6.8	1981
KENS	KEK/Japan	500 × 7	3.5	1980

In the U.S., site-specific studies of 1-MW pulsed spallation sources, begun in 1992 at ANL and Los Alamos National Laboratory (LANL), have been documented and reviewed. BNL has documented a preliminary study of a green field 5-MW source, and LANL has begun a study of a 1-MW long-pulsed spallation neutron source to be based on the LAMPF beam. In early 1995, DOE designated ORNL as the preferred alternative site for a 1-MW pulsed spallation source, on which design studies are to begin in FY1996. Europe, Russia, and Japan also have ongoing studies of comparable sources at various stages of completion.

D. 4. 2. Synchrotron Light Sources

The increasing availability of synchrotron radiation has revolutionized many fields of basic research, including chemistry, materials science, and structural molecular biology. It has also had major benefits for applied research, such as the development of techniques for lowering detection limits of contaminants on silicon chips. In medicine, clinical studies are under way on coronary angiography without the conventional, invasive arterial catheter.

Some specific fields of study include IR and X-ray microscopy, surface science, atomic and molecular physics, magnetic circular dichroism, spin-polarized photoemission, lithography and micromachining, diffraction, EXAFS, magnetic scattering, liquid surfaces, standing waves, angiography, structural biology (crystal structures and EXAFS), resonant nuclear scattering, trace element analysis for semiconductors, environmental science, photoelectron diffraction, spectromicroscopy, electronic structure (band structure, semiconductors, superconductors), and X-ray crystallography (materials and proteins).

Synchrotron light source performance has increased greatly with advances in accelerator and insertion device technology. The increase has been particularly dramatic for the flux (number of photons/s -mrad -0.1% bandwidth), brightness (number of photons/s -mm^2 -$mrad^2$ -0.1% bandwidth), and coherence (proportional to brightness) of VUV and X-ray beams. X-ray source brightness has increased by about 11 orders of magnitude during the past 25 years.

The first major increase in brightness, of about five orders of magnitude, occurred in the 1970s with the parasitic use of synchrotron radiation from the bending magnets of storage rings developed for high energy physics research—the so-called first-generation rings. Subsequently, fully dedicated light sources, the second-generation rings, were brought on line in the 1980s. These offered many beamlines, primarily from bending magnets, in facilities designed from the start as light sources. With the implementation of insertion device sources on first- and-second generation rings, starting in 1979, it became clear that the brightness could be significantly increased if the electron beam emittance were reduced. This led to the design and construction of the third-generation rings, with many straight sections for insertion devices and with lower emittance than earlier rings. Third-generation rings are now coming on-line around the world. BES now supports one first-generation facility (SSRL), one second-generation facility (NSLS), and two third-generation facilities (ALS and APS).

In addition, major new source capabilities, leading to new scientific opportunities, have emerged with the very active development of insertion devices. These include higher flux at high photon energies with superconducting wigglers, higher brightness at high photon energies with small-gap, short-period undulators, and circularly polarized beams with switchable helicity. Major progress has also been made in developing compensation schemes to permit the undulator on an individual beamline to be tuned without adverse effects on other beamlines.

Nonetheless, as powerful as third-generation sources are, fourth-generation sources with even higher performance appear achievable, since we are far from fundamental limits such as the diffraction limit, particularly at X-ray wavelengths. The ease with which this generation of sources has been commissioned has led to consideration of fourth-generation light sources at several laboratories. These include designs for advanced storage rings with lower emittance, shorter bunches, and/or longer straight sections.

D. 4. 3. Free-Electron Lasers (FELs)

FEL user facilities, primarily in the near-IR, are now in operation in several laboratories around the world, including four in the U.S. These have proved to be extremely capable sources, opening up new scientific opportunities with bright, coherent IR beams. Since these are still relatively new sources, many ideas have been proposed for extending their performance and spectral range.

A study done by the National Research Council in 1994 concluded that “the most compelling case for a free-electron laser facility is in the far-infrared, the region between 1000 and 10 µm.” This report also recommended that “the development of technology for a vacuum ultraviolet free-electron laser should be supported” and that “the research and development necessary for the possible construction of an X-ray free-electron laser should be supported.” This report repeatedly stressed the need for R&D to develop more compact FELs and to reduce their cost. (See *Free-Electron Lasers and Other Advanced Coherent Light Sources,* report available from the Board on Chemical Sciences and Technology, National Research Council, 2101 Constitution Avenue, Washington, DC 20418.)

Around the world, activities are under way at accelerator laboratories to extend FEL operation to wavelengths shorter than the 240 nm reached to date. Duke University, Dortmund University, and the Photon Factory group at the KEK laboratory in Japan are pursuing oscillator configurations in which an optical cavity is used to build up the intensity of the radiation. However, because of the lack of suitable reflecting materials, it is difficult or impossible to make such a cavity with high enough reflectivity at wavelengths below about 150 nm.

This has led to the development of the single-pass, high-gain amplifier approach in which laser operation is achieved in a single pass of a bright electron beam from a linear accelerator through a long undulator. With advances in accelerator technology, it now appears possible to use high-energy linacs to extend FEL operation down to wavelengths in the angstrom range. These advances include the development of high-brightness electron sources, initially at LANL; advances in the understanding and control of emittance degradation effects in the acceleration and compression of high-brightness beams, initially at SLAC; and the development of precision undulator magnets, initially at LBNL. These sources would deliver sub-picosecond X-ray pulses with coherent power and instantaneous brightness many orders of magnitude higher than that available from third-generation rings. However, such linear light sources would have a slower repetition rate and serve a smaller number of users than light sources based on storage rings.

Proposals for linac-based short-wavelength FELs have been developed at BNL ($\lambda > 750$ Å, using a 210-MeV linac) and SLAC ($\lambda > 1.5$ Å, using a 15- to 20-GeV linac). The DESY laboratory in Hamburg, Germany, is constructing a single-pass FEL that would reach about 60 Å using the TESLA Test Facility 0.5- to 1.0-GeV superconducting linac. Short-wavelength FELs are also being considered at CERN and at several laboratories in Japan.

D. 4. 4. Funding

The total BES budgets for FY1995 and 1996 are $705.3M and $738.1M, respectively, including funding for Applied Mathematical Sciences and Advanced Energy Projects. The corresponding operating budgets are $601.1M (FY1995) and $660.0M (FY1996). Of the total, 30% was devoted to accelerator-based facilities in FY1995; 26% is projected for such facilities in FY1996.

D. 4. 5. Users Of Synchrotron Radiation and Spallation Neutron Facilities

The BES-funded accelerator-based synchrotron radiation and neutron-scattering user facilities support a large number of users from universities, industry, government laboratories, and foreign institutions. Details are given in the table below. These users receive support from many sources, including BES and other DOE offices, other agencies, industry, and foreign sources. Most of the BES support comes through the BES Divisions of Materials Sciences and Chemical Sciences. Of all the individual research projects supported by the former division, about 25% use accelerators in some form, including electron microscopes. For the Division of Chemical Sciences, this number is about 10%.

The user community for neutron sources has not grown significantly in recent years, not because of limited demand, but rather because of static funding for the operation of existing facilities. Where user programs exist and where the program of utilization is through a proposal-and-review system, the facilities are always oversubscribed by factors of two or three. This frustrating situation has been recognized recently, and measures to rectify it are reflected in the Scientific Facilities Initiative, now approved by the Congress and the President. This Initiative will provide sorely needed increases in operations support for synchrotron light and neutron sources operated by the DOE, as well as for high energy and nuclear physics facilities.

Light source and neutron source experiments are “small science” efforts. A typical team consists of two or three scientists, who bring an experiment to the facility. Measurements last a few hours, a few days, or in some cases, a few weeks. Several classes of users can be distinguished: (i) specialists, typically resident at the facilities, who provide, care for, and operate instruments for users and who may team up with incoming users or carry out scientific programs of their own; (ii) experts who are thoroughly conversant with the techniques and instruments being used and who usually carry out measurements and analyses independently; and (iii) occasional users, less familiar with the techniques but requiring data from the facilities that cannot be provided by other methods. User support, particularly for this last category of user, is an important service provided by each facility, or by the research team responsible for the beamline.

All three categories of users typically take advantage of other spectroscopies in their scientific programs, so that the neutron or light source represents only one of several research methods available, others of which are accessible at home installations. Users travel from one large installation to another, as science demands, to capitalize on special features available in different places. Since, to a large extent, light source and neutron source experiments are “scattering” measurements, the same scientists often use both types of facilities in their programs.

User Community for BES-Supported Synchrotron Light and Pulsed Neutron Sources

(Data for FY1994)

	University	Industry	Labs	Other	Total
Light Sources					
NSLS	1097	317	449	368	2231
SSRL	324	58	155	50	587
ALS*	(61)	(5)	(72)	(25)	(163)
Subtotal	1482	380	676	443	3073
Pulsed Neutron Sources					
IPNS	63	15	62	32	172
LANSCE**	15	5	36	17	73
Subtotal	78	20	98	49	245
Total	1560	400	774	492	3318

* ALS is still in a start-up mode, with new beamlines being implemented. Figures in parentheses refers to the latest 12-month period. APS is currently being commissioned.

** LANSCE operated for only 1 month in 1994.

D. 4. 6. Electron Microscopy

In support of its mission, the DOE also funds electron microscopy centers. Electron microscopy plays a major role in materials research, including research on energy-related materials. More than a third of all papers published in materials sciences journals involve electron microscopy in some way. Because electron microscopes are based on accelerator technology, we included a brief description of this activity here.

The DOE funds four electron microscopy user facilities: the National Center for Electron Microscopy (NCEM) at LBNL, the Electron Microscopy Center for Materials Research (ECM) at ANL, the Shared Research Equipment (SHaRE) program at ORNL, and the Center for Microanalysis of Materials at the University of Illinois, all with annual operating budgets under $2M. Together, these four facilities provide specialized facilities for forefront research projects and serve a user community of more than 800 scientists a year. A far larger number of researchers, not requiring state-of-the-art facilities, make use of thousands of small, commercially available electron microscopes in individual research labs.

The major new directions in instrumentation are concerned with electron optics, computer image reconstruction, and the development of stages and detectors. The facility most closely involved with accelerator technology is the one at ANL, where a tandem accelerator is interfaced with an electron microscope for in situ ion irradiation experiments.

D. 5. Health and Environmental Research

The program mission of the Office of Health and Environmental Research (OHER) is to develop and support fundamental science that underpins the strategic goals of the DOE in areas related to health and environmental effects. The OHER program "develops the knowledge needed to identify, understand, and anticipate the long-term health and environmental consequences of energy production, development, and use." Accordingly, OHER pursues three overall strategic objectives:

- To contribute to human health by: sequencing the human genome by 2005; developing advanced medical technologies and radiopharmaceuticals; and using unique national laboratory facilities for structural studies at the molecular and cellular level.

- To contribute to cleaning up the environment by developing advanced remediation tools and risk assessment technologies.

- To understand global environmental change by understanding the role of energy production.

Explicit operations support for accelerator-based facilities and R&D support for related technologies are not parts of the mission orientation in OHER (as they are, for example, in BES in its operation of synchrotron light sources). However, the long-term strategic directions of OHER are problem-oriented, and accelerator-based technologies offer a *means* to help solve specific problems. In particular, OHER supports the development of specialized capabilities at national laboratories that enable researchers to make use of these unique facilities. These capabilities take the form of beamlines and/or instruments at the DOE synchrotron light sources and accelerator-based neutron sources (and also reactors). Key components of OHER's strategy include support of scientific and technical personnel to construct, operate, and provide user support for the specialized instrumentation. An additional important component is the provision of funding for advanced R&D, especially detector R&D. The shared facilities supported by OHER are used by hundreds of scientists from the national laboratories, universities, and industry. Funding for the individual research projects conducted at those facilities often comes from other agencies, especially the NIH and the NSF. In some cases, close cooperation between OHER and the NIH has led to the development of complementary resources at the facilities, to the direct benefit of the user community.

D. 5. 1. Structural Molecular Biology

The area of structural molecular biology is of central importance in sequencing the human genome and in understanding how this information can be used for improving health. Obtaining an in-depth knowledge of molecular structure is closely coupled to understanding the function (and malfunction) of biological processes. Such structural knowledge comes primarily from studying how biological molecules interact with electromagnetic radiation or neutrons.

As noted earlier in this appendix, synchrotron radiation provides remarkably intense X-rays broadly applicable to the study of condensed matter. In the field of structural molecular biology, synchrotron radiation offers the means to solve more challenging problems (for example, the study of larger structures and assemblies) with higher resolution (even at the level of individual atoms) and to do it more rapidly than is possible with conventional sources. For scientists to make use of synchrotron radiation, however, specialized facilities must be developed and supported for studying biological systems. Accordingly, OHER is funding ongoing programs at NSLS and SSRL and has initiated projects (currently in the construction phase) at the ALS and the APS.

Growth in the demand for access to synchrotron radiation facilities for structural biology research has been remarkable. In the early 1980s, synchrotron radiation was little used for such studies; it was applied primarily to specialized problems being studied by a few small groups. From 1980 to 1990, however, the use of synchrotron radiation grew rapidly, revolutionizing several areas, including time-resolved investigations of biological structure and high-resolution studies of very large biological assemblies such as viruses. By 1991 a survey of biological users of synchrotron radiation revealed that existing facilities were oversubscribed and "a threefold increase in the need by U.S. scientists for synchrotron radiation is projected through the year 2000, based on current growth rates."

Because of the unique capabilities at the national laboratories for synchrotron radiation–based science and because of the direct relevance of these technologies to the OHER mission, OHER proposed and initiated a program to develop the resources and to provide support for access by the biological community. This approach was strongly endorsed and supported by the 1992 review of structural biology by a subcommittee of the Health and Environmental Research Advisory Committee (HERAC). This endorsement was reaffirmed in a more recent review (September 1995) of the OHER instrumentation programs (which includes synchrotron user facility support) by another HERAC subcommittee. Nonetheless, it is by no means clear that the new beamline developments currently funded by OHER at SSRL, the APS, and the ALS will meet the continually increasing user demand.

Compared with studies using synchrotron radiation, neutron scattering and neutron crystallography serve a complementary and, in some ways, more specialized role in studies of biological systems. Hydrogen atoms (which are involved in hydrogen bonds common in biological structures) can be located precisely with neutrons, but not with X-rays. Neutrons also provide special capabilities for enhancing contrast of a selected component in a large biological assembly. OHER therefore supports development of neutron-scattering expertise and capabilities for the study of biological macromolecules at the LANSCE pulsed neutron-scattering facility at LANL. (It also supports similar efforts at the steady-state reactor facilities at BNL and ORNL.) In all of these cases, OHER again supports specialized facilities and staff for R&D and user support, not facility operations and accelerator development.

D. 5. 2. Environmental Sciences

There is an increasingly pressing need to study and understand the chemical and physical forms of toxic and radioactive contaminants and pollutants in soils, sediments, man-made waste forms, natural waters, and the atmosphere. This information is important in understanding why contaminants do (or do not) migrate and in helping to develop sound remediation strategies for removing these materials from the environment. Techniques using synchrotron X-rays (especially X-ray absorption spectroscopy and X-ray scattering techniques) have significant potential to provide the needed scientific information. Existing synchrotron facilities at NSLS and SSRL are already being used in this regard, and development of new specialized facilities is being considered by OHER to support basic research in this area. As these endeavors utilize BES-operated synchrotrons and are of direct interest to the mission of EM, coordination across these offices is essential. This area was examined in a DOE workshop held in July 1995, entitled “Molecular Environmental Science:

Speciation, Reactivity, and Mobility of Environmental Contaminants—An Assessment of Research Opportunities and the Need for Synchrotron Radiation Facilities."

D. 5. 3. Nuclear Medicine

Nuclear medicine is the practice of using radioactive isotopes for diagnostic imaging, the measurement of physiologic processes, and the treatment of disease. Radionuclide imaging has been widely used for diagnosing brain and heart disease, and for diagnosing and treating many types of cancer. Nuclear medicine has applications in practically every organ system in the body, and is also useful in evaluating patient response to therapy. An estimated one-third of hospital patients in the U.S. undergo nuclear medicine procedures, and even more nuclear medicine procedures are performed on outpatients.

More that 50 different types of diagnostic tests involve nuclear medicine. These include radioisotopes administered to patients with disorders affecting bone, heart, lung, brain, thyroid, kidney, liver, gall bladder, and the colon. In all cases, accelerators and reactors produce the radioisotopes used to perform the tests. Most accelerator-produced isotopes used in clinical practice are supplied by commercial sources using relatively low-energy cyclotrons (30 to 50 MeV). Isotopes requiring higher energies (greater than 50 MeV) are obtained from DOE accelerator facilities such as BLIP, LAMPF, and TRIUMF (the last of these in Canada). Most isotopes produced with these higher-energy accelerators are used in research, with only a few used in clinical medicine. In addition, a few of the medical centers around the country own and operate small, low-energy cyclotrons (10 to 15 MeV) to supply very-short-lived isotopes for their positron emission tomography (PET) programs. OHER does not directly fund the operations of any of these accelerator facilities except a contribution the BLIP program makes to the operation of the AGS's linac injector. It does, however, support R&D on the fundamental aspects of radiopharmaceuticals and radionuclides. OHER also provided the construction funding for upgrading the BLIP complex at BNL in 1994 and funded an R&D effort emphasizing target development for high-intensity operation and optimized radioisotope processing.

D. 5. 4. Funding and Users

The total OHER budget for FY1995 was $431M. Of this total, about 7% was devoted to activities that relied on accelerator-based capabilities for structural biology and nuclear medicine.

The users of OHER-supported beamlines and instruments are included in the table summarizing users of BES-funded synchrotron light and neutron sources in Section D.4.5.

D. 6. Fusion Energy

The goal of fusion energy research is the production of controlled fusion energy for electric power generation. Accelerators play important roles in fusion research supported by the OER and in the inertial confinement fusion (ICF) program supported by the DOE Office of Defense Programs. The three principal roles in OER are: plasma heating for magnetic fusion energy (MFE), drivers for inertial fusion energy (IFE), and materials testing. All three have the potential of being critically important to the fusion program, but support has not been steady.

D. 6. 1. Plasma Heating

Neutral-beam accelerators for plasma heating enabled the Tokamak Fusion Test Reactor (TFTR) at Princeton to achieve a world-record fusion power level of approximately 10 MW. Despite this success, the Office of Fusion Energy (OFE) recently terminated the U.S. neutral-beam research program. The U.S. fusion community is a collaborator in the proposed construction of the International

Thermonuclear Experimental Reactor (ITER). The plans for ITER are still evolving, and neutral beams may yet be needed. Japan has maintained a large neutral-beam research program and is likely to supply any neutral beams needed for ITER.

D. 6. 2. Inertial Confinement and Heavy-Ion Fusion

Defense Programs sponsors the inertial confinement fusion program primarily for its applications to weapons physics and nuclear stockpile stewardship. In ICF intense laser or ion beams will be used to implode and ignite millimeter-sized capsules containing thermonuclear fuel. The burning fuel will produce many times the amount of energy used to implode and ignite the capsule. To achieve ignition, however, the beams must deposit several megajoules of energy in about ten nanoseconds. These numbers correspond to a beam power of several hundred terawatts. Lasers can readily produce high beam power and are, therefore, well suited to near-term research on the physics of the fusion capsules. Accordingly, the DOE and Congress recently approved construction of the National Ignition Facility (NIF) which is a billion-dollar laser facility for defense-related ICF research. The NIF schedule calls for demonstration of thermonuclear ignition in the year 2005.

The NIF and other existing lasers do not have some important capabilities needed for commercial power production. They do not have the pulse repetition rates, the lifetime, the reliability, or the efficiency needed for economical power production. Review panels have consistently identified high-energy heavy-ion accelerators as the most promising driver technology to solve these problems. Heavy ions, in contrast to light ions, give the appropriate depth of penetration at ion kinetic energies achievable by conventional accelerator technology. The principal new issue for heavy-ion inertial fusion is the production of very high beam power while maintaining adequate beam quality for focusing. Theory, numerical simulation, and scaled experiments indicate that it should be possible to produce beams with adequate power and quality, but further progress reqires experiments with full-scale beams.

LBNL has proposed the construction of a series of such experiments, known collectively as ILSE (Induction Linac Systems Experiments). Multiple beams of ions such as potassium or cesium would be accelerated to a kinetic energy of about 10 MeV. Elise, a 5-MeV accelerator using electrostatic focusing is the first phase of the ILSE program. In December 1994, OFE approved the construction of Elise, with construction scheduled to begin in FY1996, but Congress did not approve any new OER fusion projects. At this point, the future of the Elise project is unclear. It would be desirable to complete the accelerator research program by 2005 so that the combination of data from NIF and the accelerator research program could be available to make a sound decision about the feasibility of heavy-ion fusion.

Heavy-ion fusion is a good example of (i) a benefit that has emerged unforeseen from accelerator developments undertaken for high energy physics and (ii) strong synergism among DOE programs. If successful, heavy-ion fusion will provide an important source of energy for future generations. One of the most critical issues facing OER is the projected cost of developing fusion science and technology. The development of heavy-ion fusion is expected to be relatively inexpensive, because other accelerator programs have developed much of the technology, for example, superconducting magnets, high-power switching technology, and accurate alignment systems, and because Defense Programs has developed much of the target science. Ongoing developments in these areas will undoubtedly continue to benefit heavy-ion fusion.

D. 6. 3. Materials Testing

Materials testing, the third major role of accelerators in OER's Fusion Program, has a long history. Fusion researchers have recognized for more than two decades that the development of advanced materials is needed to make magnetic fusion environmentally and economically attractive. One critical issue is the behavior of these materials under bombardment by fusion-spectrum neutrons (14 MeV for deuterium-tritium fuel).

In 1992, OER asked the Fusion Energy Advisory Committee to review OFE's Neutron-Interactive Materials Program. The resulting report (DOE/ER-O593T), issued in April 1993, emphasizes the need for a neutron source to test fusion materials and concludes that an accelerator-based system provides the most direct route to the needed capability. The report states that preparation for building a demonstration power plant "requires that both ITER and a high-flux 14-MeV neutron source proceed on similar schedules. Two concepts have been proposed: a 35-MeV deuterium beam impinging on a liquid lithium target, and a 120-keV deuterium beam impinging on a mirror-plasma target. While the proposed accelerator technology for a D-Li neutron source will be challenging (especially if superconducting RF cavities are chosen), the beam current exceeds existing room-temperature CW systems by only a factor of two and appears feasible. Although the design of the lithium target system will be difficult, much was accomplished in the earlier FMIT Project. This approach appears to be the most direct route to attaining the needed materials testing capability."

Funding for the Fusion Material Irradiation Test (FMIT), mentioned in the quotation above, reached a peak of nearly $31M per year in FY1981. The DOE had hoped for foreign contributions to FMIT, but these contributions did not materialize, and construction was canceled. The international fusion community is now developing plans to design and build a new facility, usually called the International Fusion Materials Irradiation Facility (IFMIF) for materials testing. The probable cost is near $1B.

D. 6. 4. Other Aspects of Accelerators and Fusion Research

Apart from these three main applications of accelerators to fusion, the nuclear data obtained from accelerators are an indispensable part of the foundation of fusion research. These data include cross-sections for fusion, for tritium production, for the activation of materials, and for the interaction of heavy ions with matter. In addition, accelerator technology is the basis for some speculative approaches to fusion, such as colliding-beam machines, and accelerator spin-off technologies such as superconductivity, RF power production, and diagnostics all find important applications in fusion research.

Other accelerator programs provide important contributions to the OER fusion program. Examples include the Rotating Target Neutron Source (RTNS) facility at Lawrence Livermore National Laboratory (LLNL), Defense Programs' light-ion fusion research, and U.S. Department of Defense accelerator research. The RTNS is a high-current, continuous-beam deuteron accelerator producing D,T neutrons in a rotating, tritiated metal target; it has provided important data for Defense Programs' fusion effort. Light-ion fusion research is strongly related to the heavy-ion fusion program through beam physics, target physics, and pulsed-power technology. The work sponsored by the Defense Department is related through beam physics, precise focusing systems, and the development of advanced accelerator concepts.

D. 6. 5. Funding and Users

Funding for magnetic fusion energy in FY1996 is approximately $236M; this is about $120M below the FY1995 appropriation. FY1996 funding for inertial fusion energy is $8M.

Unlike the situation in High Energy Physics, Nuclear Physics, BES, and OHER, fusion accelerators have not yet become large user facilities. In the case of beam heating, the accelerators are essential parts of larger devices. The larger device, for example, the Tokamak Fusion Test Reactor (TFTR) or Doublet III-D (DIII-D), may serve a number of users, but this practice is not as common as in the other fields. At the present time, the issues for heavy-ion inertial fusion are related to the accelerator itself, and the accelerator designers and builders are themselves the users. Ultimately, a full-scale heavy-ion driver would be capable of serving a large user community doing research on targets, target chambers, materials, etc. A fusion materials test facility would, from its inception, be a user facility.